Physical Reasoning of Interconnection Forces for Efficient Assembly Planning

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Abstract

Many of the approaches proposed to date for assembly planning have focused on the geometric reasoning of path interferences among parts to generate assembly sequences efficiently. However, we find that the physical reasoning of interconnection forces (torques) required for mating operations also plays a very important role in determining assembly planning. In this paper, we explore methods for accomplishing physical reasoning of interconnection forces required for assembly and incorporate the results into the assembly planning. The physical reasoning of interconnection forces allows part merging for subassembly identification which helps to avoid many computations required for geometric reasoning and thus enhances the efficiency of assembly planning.

1 Introduction

The approach to the problem of assembly planning is based either on the forward search of feasible, assembly sequences [1] or backward search of assembly sequences in the form of disassembly planning[2,3,4]. No matter which approach is taken, the problem is basically a search problem that is subject to the satisfaction of certain precedence relationships or infeasibility conditions for assembly or disassembly due to the topological or geometrical constraints. One approach is to develop an interactive system in which minimal questions are formulated and based on the responses of the designer the specification of precedence relationships for searching is completed[5,6,7]. The other approach is to develop a planning system that can do the automatic reasoning of geometric interference and path planning for the test of infeasibility conditions for assembly planning [8,9,10]. However, usually such geometric reasoning is quite computationally expensive and the complexity may grow exponentially as the number of the parts increases. One of the current research is thus to achieve the efficiency by the method such as logical inference to avoid unnecessary tests [9,11].

In order to bring the assembly planning closer to the real world environment, some other factors that affect the assembly planning in addition to the geometric reasoning for part mating should also be taken into account. A very important and practical factor to be considered is the interconnection form or torque requirement during the assembly operation. This factor not only affects the completeness of assembly operation but also the stability problem which subsequently will affect the. assembly planning. The research on the specific problems of subassembly stability under the existence of gravity or external forces has also been addressed in some literatures[12], but the incorporation of this factor into the consideration for the generation of assembly planning seemed still lark of.

This paper presents a simple way to take the interconnection forces into account while generating the assembly planning. The approach for generating the assembly planning is based on the method proposed by S. Lee called Backward Assembly Planning (BAP). The BAP method finds the. feasible assembly sequences by reversing the disassembly sequences obtained through the recursive decompositions of all assembly into valid subassemblies [13]. By such physical reasoning of the interconnection forces for the test of interconnection feasibility, much computation efforts for the tests of geometric interferences can be avoided in advance to increase the planning efficiency.

2. Interconnection Feasibility

Consider a very simple hypothetical example in Fig.1 in which P1 is connected with P2 by "loose fit" while P2 is inserted into P3 by "forced fit" and a cover P4 will be placed on the base of P1 and welded to P3. If we consider only the geometric constraints without considering the required interconnection force for the assembly task, most of the developed assembly planning methods will generate three "feasible" assembly sequences as shown in Fig 2.

It is obvious that even though sequence 1 is a feasible one, additional fixture or holding device is needed to stabilize the subassembly {P1,P2} to assemble P3. This type of undesirable assembly sequences maybe discarded after the assembly cost evaluation. However, if the interconnection force required for assembly task is not considered, some infeasible assembly sequences maybe generated such as sequence 2 in Fig.2. Thus the interconnection feasibility condition is required and is important because bringing parts to their mating positions without any geometric interference is not enough. Usually external forces or torques are needed to exert on the parts to complete the assembly task and the interconnection feasibility will also affect the. assembly sequences.

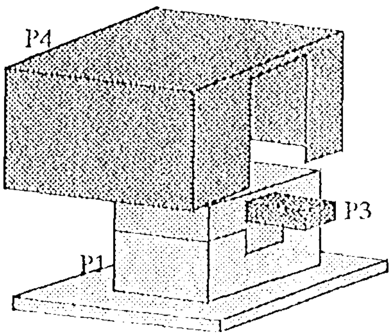


Fig. 1. A hypothetical assembly to illustrate the interconnection feasibility.

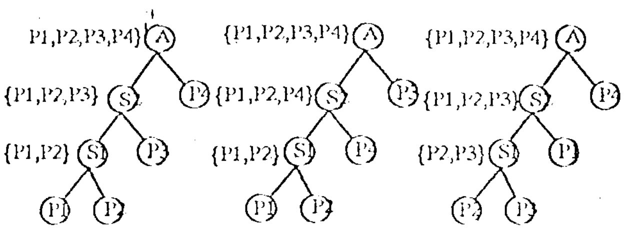


Fig. 2. Possible assembly sequences for the assembly in Fig. 1.

2.1 Interconnection types

in order to analyze the required interconnection fmcc for interconnection feasibility, we categorize the interconnection types of liaisons into four types:

(1) Pure-Contact Interconnection:
The interconnection of the parts is completed by simply bringing the parts to their mating position and contact to each other without exerting any external force to the parts to establish the interconnection such as "Place-on" type of interconnection.

(2) Forced-Contact Interconnection:
The interconnection is completed by exerting force or torque to one or both of the park to establish the interconnection, for instance, the "Force-fit" type of interconnection.

(3) Medium-Contact Interconnection:
The interconnection is completed by pure contact and some other media which are considered as connectors rather than a part in assembly planning. For example, two pails arc. connected through the "connectors" such as "pin", "screw", "bolt" or "rivet".

(4) Mixed-Contact Interconnection:
The interconnection of the liaison is completed by both applying force 10 the parts and by the reinforcement of the connectors.

in this categorization, some parts whose function is simply to connect other parts are considered as connectors instead of parts and are treated separately in assembly planning. The reasons to do such distinction are:

(1) Sometimes there are many parts used as connectors in an assembly. The exclusion of this kind of parts from regular par ts can reduce the number of park considered in assembly planning dramatically which will increase the efficiency of the assembly planning.

(2) Because of the specific function of connectors, usually the assembly task and the installing tools can be considered separately in a much simpler way.

Usually parts such as screws, blots, pins, rivets, even welds etc. are considered as connectors.

2.2 Interconnection Feasibility Consideration in BAP

The core of Backward Assembly Planning (BAP) is the process which recursively identifies and selects preferred subassemblies called direct subassemblies [13]. In other words, the process recursively finds the valid cut-sets of the liaison graphs without violating some necessary and sufficient conditions such as accessibility, interconnection feasibility, geometric interference conditions, special process coil.straillts etc. Some of the. tests of the.se conditions are very time consuming, for instance, the geometric reasoning for the interference checking. In order to increase the efficiency, these conditions arc tested hierarchically. In BAP, the interconnection feasibility is chosen to be test first because it involves only one individual liaison at a time so that the computation is much simpler than other tests. A preprocess called merging process to test the interconnection feasibility is developed and discussed in next section. Through this preprocess, the. original liaison graph can be transformed into a much simpler form so that the number of those computationally expensive tests can be dramatically reduced and increase the efficiency of assembly planning.

3. Part Merging Process

The merging process is basically to identify each liaison in liaison graph, $G_L(A)$, that violate the interconnection fusibility condition and merges those parts associated with that liaison. Through this merging process, three purposes

are achieved:
(1) The interconnection feasibility condition is tested.
(2) The generated assembly sequences are reversible.
(3) The liaison graph is simplified to increase efficiency.

3.1 Interconnection Feasibility Condition Test

According to the categorization in section 2.1, whether or not the interconnection of a liaison between two parts can be completed is determined by the satisfaction of following two conditions:

Condition I:

The feasibility of applying and operating tools for installing the connectors required for the interconnection of the liaison.

Condition II:

The feasibility of applying the forces, while maintaining the stability, required for the establishment of the interconnection.

3.1.1 Testing of Condition I

The test of condition I is needed for liaisons of interconnection types with connectors. The test is done by checking the existence of open channel to the designated location, through which the tool can operate to install the connectors without geometric interference. This can be easily achieved because of the special features and function of connectors and the tools needed to install the connectors. The algorithm to test the interconnection feasibility for the liaison using connectors is shown in Fig. 3.

Step 1: Check the types of connectors (revolute or translation).

Step 2: Define the operation space (volume), V_{op}, according to the volumes of connectors and the tools required to install the conductors.

Step 3: Determine the approaching direction (path), D_{op}, according to the orientation and position of connectors and installation of the operating tools.

Step 4: Check if interference occurs by sweeping V_{op} along D_{op}.

Fig. 3. Algorithm for interconnection test of liaison using connectors.

3.1.2 Testing of Condition II

The test of condition II requires the reasoning on the force propagation to a liaison through other intermediate liaisons. In order to consider the force delivery through the liaisons, we classify the liaisons into three classes:

(1) Floating Liaisons:

A liaison is said to be floating if there exists no physical force holding the parts associated with that liaison together. A liaison of purely-contact interconnection type. is a floating liaison.

(2.) Rigid Liaisons:

A liaison is said to be rigid if there exists physical force holding the associated parts together, or there exists other medium like the connector holding the parts together, by which the liaison becomes self-stable even under the presence of external forces. For instance, a liaison of forced-conflict interconnection type like "force-fit", or a liaison of medium-contact interconnection type like "rivet-connection" may be classified as a rigid liaison.

(3) Weak-Rigid Liaison:

A liaison is said to be weak-rigid if there exists a physical force holding the associated parts together, by which the liaison becomes self-stable. The distinction between rigid and weak-rigid liaison is that under the presence of certain amount of external forces, weak-rigid liaison may exhibit a deformation or a freedom of motion. For example, a "loose-fit" interconnection liaison may result in a freedom of motion if the external force exceeds the holding force (friction) between the two parts.

The distinction between rigid and weak-rigid liaison is done by specifying a threshold. The liaison with holding force larger than the specified threshold is classified as rigid liaison otherwise it is classified as weak rigid liaison. The threshold can be specified by the designer. For example, the threshold can be specified as the maximum interconnection force required among all the liaisons.

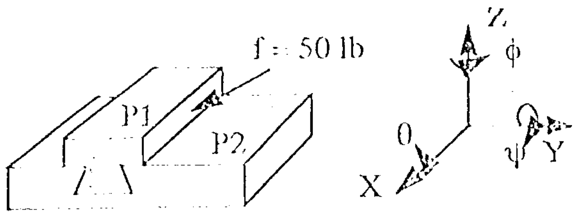
3.1.3 Force Delivery Through Liaisons

In order to consider the force propagation through the liaisons, the local freedom of motion (*LFM*) associated with a liaison should be determined first. The local freedom of motion of a liaison l_i connecting P1 and P2, *LFM* (l_i), is represented by the relative freedom of motion of P1 against P2 or relative freedom of motion of P2 against P1, i.e., *LFM* (l_i;P1|P2) or *LFM* (l_i;P2|P1). The research on determining the local freedom of motion for separation of two parts is also an interesting and active field. Lots of works have been done in this areas. In this paper, we are not going to discuss it in detail. In general, the local freedom of translation motion of a part in three dimension takes the form of a convex cone.

While considering the interconnection feasibility, the local freedom of motion of a liaison is not only determined by the geometric constraints but also the physical force existing in the liaison that holds *the* parts. To take the physical force into account, the *LFM* of a liaison is generalized to include this information. A generalized local freedom of motion (*GLFM*) of a liaison can be represented as:

$$GLFM\ (l_i; P1|P2) = (LFM\ (l_i; P1|P2), F)$$

where $LFM\ (l_i; P1|P2)$ is the space of possible directions of separation of P1 relative to P2 determined by geometric reasoner. F is the required external force or torque to establish (or break) the liaison in that space of directions of separation. For a floating liaison $F=0$, for a rigid liaison $F = \infty$ and for a weak-rigid liaison $F = f$ where f is the force or torque required to establish or break the liaison. The $GLFM$ of a weak-rigid liaison is illustrated in Fig.4.



$$GLFM\ (l_i; P1|P2) = \{(+X, 50\ \text{lb}), (R^3-(+X), \infty)\}$$
$$: \{(+X, 50\ \text{lb})\}$$

Fig.4. GLFM of a weak-rigid liaison

Now in order to test condition II, following definitions are introduced for the test of feasibility of applying force required for the interconnection of liaison l_i.

Definition: Accessible Node, A-Node

A part is accessible if it is reachable and graspable by a tool for the assembly operation. A node is accessible if any one of the parts that form the node is accessible.

Definition: Accessible Path to a node n, A-path(n)

An accessible path to a node n is a path starting from an A-node and ending with the node n without having any other A-node in the middle of the path. Following are the properties associated with an A-path:

* A- node has an A-path to itself.
* A node n may have one or more A-paths.
* An A-path is represented by an ordered set of the liaisons of parts on the path.
* Independent A-paths: two A-paths are said to be independent if they share no common parts.

Definition: Generalized Internal Motion Space GIM[A-path(n)], of an A-path(n).

The generalized internal motion space of an A-path (n) is defined as the union of the generalized local freedom of motion of all liaisons in the A-path(n). The generalized internal motion space represents the flexibility that the configuration of parts along the A-path(n) can be deformed by an external force, with first part (corresponding to A-node) and last part fixed in space. Assume that an A-path(n) is represented by an ordered set of liaisons, $\{l_1, l_2, \ldots l_r\}$, with l_i formed by a pair of nodes, (n_{i1}, n_{i2}) and that (n_{i1}, n_{i2}) is ordered along A-path(n) in the direction toward n. The GIM[A-path(n)] $= \bigcup_{i=1..r} GLFM\ (l_i; n_{i1}|n_{i2})$.

Definition: Force-Deliverable A-path(n).

Due to the orthogonality between motion space and force space, a force f can not be delivered through a liaison in the directions within the $GLFM$ of that liaison if $f > F$. Thus an A-path (n_{ij}) is said to be force deliverable to n_{i1} for the liaison l_i of (n_{i1}, n_{i2}), if

(1) $f \notin GIM$[A-path (n_{i1})] or

(2) $f \in GIM$[A-path (n_{i1})] and $f < F$

where f is the force or torque required for the interconnection of (n_{i1}, n_{i2}).

With these definitions, condition II for interconnection feasibility of a liaison of (n_{i1}, n_{i2}) can be transformed into the unification of the existence of an independent force-deliverable A-path for n_{i1} and n_{i2}.

3.2 Reversible Assembly Sequences

As pointed out in the beginning, one approach to generate the assembly sequences is to find the disassembly sequences of a given assembly and reverse it. However, this reversing process to generate assembly sequence is not always correct. In other words, the reversing of some possible disassembly sequences are not feasible assembly sequences. The same situation happens where the reversing of some feasible assembly sequences are not feasible disassembly sequences. Fig. 5 shows the simple example of these irreversible sequences. Fig. 5.a shows a example that a possible disassembly sequence for this assembly is P1-> P4 ->P2-> P3 but the reverse of this disassembly sequence is not a feasible assembly because of the interconnection infeasibility between P1 and subassembly {P1,P2,P3}. Fig. 5.b shows a feasible assembly sequence as P3 -> P2 -> P1 but the reverse is not a feasible disassembly sequence due to the infeasibility to disconnect P1 with the subassembly {P2,P3}.

An assembly or disassembly sequence is called reversible if its reverse is also a feasible disassembly or assembly sequence. It would be much more efficient if the feasible assembly sequences generated by an assembly planner are reversible because all the feasible disassembly can easily be obtained at the same time by reversing simply the assembly sequences. As the example shown in Fig. 5, because of the lack of consideration of interconnection feasibility in assembly planning, the assembly sequences generated by most of the present developed methods are not all reversible. in order to generate all reversible assembly sequences, the interconnection feasibility condition test is generalized to include the tests of not only the feasibility of connection but also disconnection of a liaison. This generalization can simply be achieved by considering the required connection and disconnection fores at the same time where the forces are simply of the same amount and in opposite directions. By considering both the connection and disconnection form for the test of interconnection feasibility, the generated feasible assembly sequences in BAP are all reversible.

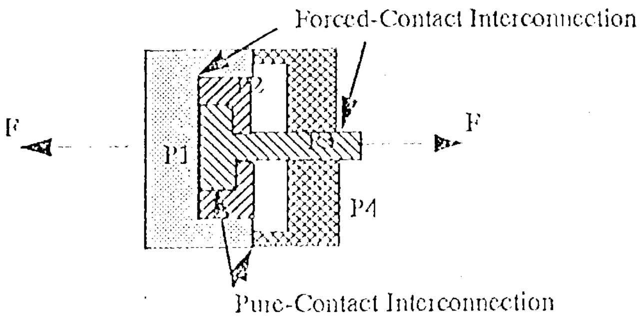


Fig. 5.a An example to show the irreversible disassembly sequence.

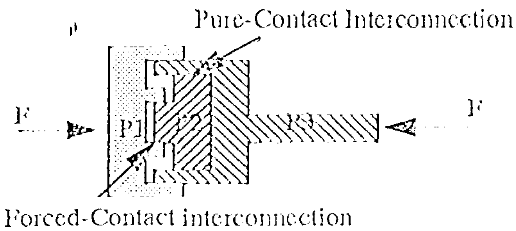


Fig. 5.b An example to show the irreversible assembly sequence.

3.3 Merging Principle

A liaison l_i of (n_{i1},n_{i2}) that violates the generalized interconnection feasibility condition tests can not be listed as a cut-set for further testing of direct subassembly, and consequently n_{i1} and n_{i2} should be merged together at current stage. A merging principle for the test of interconnection is developed which states as below:

Merging Principle

(1) For a liaison l_i (n_{i1},n_{i2}) of forced or mixed contact interconnection types, if there exists no force-deliverable A-paths for n_{i1} or n_{i2}, or no independent force-deliverable A-paths for n_{i1} and n_{i2}, then n_{i1} and n_{i2} should be merged.

(2) For a liaison l_i (n_{i1},n_{i2}) of pure or medium contact interconnection types, if there exists no force-deliverable A-paths for n_{i1} and n_{i2}, then n_{i1} and n_{i2} should be merged.

Proof

The proof is intuitive.

(p1) For a forced or mixed contact liaison, if n_{i1} and n_{i2} are interconnection feasible due to some other parts outside the A-paths of n_{i1} and n_{i2}, then the forces required for the interconnection must be propagated from some A-nodes through these parts to n_{i1} and n_{i2} independently. Thus these parts will form the independent force deliverable A-paths for n_{i1} and n_{i2}. This contradicts to the assumption that there exists no force deliverable A-paths for n_{i1} or n_{i2} or no independent force deliverable A-paths for n_{i1} and n_{i2}.

(p2) Similarly, for a pure or medium contact liaison, if n_{i1} and n_{i2} are interconnection feasible due to some other parts outside the A-paths of n_{i1} and n_{i2}, then the forces required for the interconnection must be propagated from some A-nodes through these parts to either n_{i1} or n_{i2}. Thus these parts will form at least one force deliverable A-path for n_{i1} or n_{i2}. This also contradicts the assumption that there exists no force deliverable A-paths for n_{i1} and n_{i2}.

From (p1) and (p2), the principle is proved. □

The merging principle is the sufficient condition for the interconnection feasibility test. However, the necessary condition is not always true. In other words, the existence of independent force deliverable A-paths for n_{i1} and n_{i2} does not guarantee that the generalized interconnection of n_{i1} and n_{i2} are feasible.. For example, in Fig. 6, there exists independent force deliverable A-paths for both 2 and 3 for the disconnection of l (2,3), say (1->2), (4->3). But due to the force between 2, 5, and 3, 5, 2 and 3 can not be disconnected. Generally speaking, the necessary condition for the merging principle is not true if consider the whole subassembly globally.

Although the merging principle is only the sufficient condition for the interconnection feasibility, usually it is sufficient to eliminate quite a few cut-sets of the liaison graph at each stage during assembly planning.

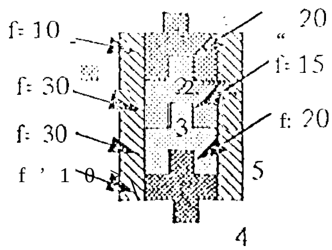


Fig. 6. An example to show the necessary condition of merging principle is not true.

A process called merging process for the interconnection feasibility test for all types of interconnection is developed. The algorithm is summarized in Fig.7.

Merging_Process ($G_L(A)$)

Step 1: Put all liaisons of $G_L(A)$ in Open-Set. Identify A-nodes of $G_L(A)$ (User or System)

Step 2: If Open-Set is empty, then Stop.

Step 3: Select and remove a liaison $l_i \sim (n_{i1}, n_{i2})$ from Open-Set in an increasing order from an A-node.

Step 4: Check interconnection type of l_i,

if $l_i \in$ {Medium-Contact or Mixed-Contact type}
goto Step 5.
else goto Step 6.

Step5: Check connector interconnection feasibility of l_i (condition I),
if False, merge n_{i1} and n_{i2}, goto Step 2.

Step 6: Check if independent force deliverable A-Paths of l_i exist
if False, merge n_{i1} and n_{i2},
goto Step 2.

Fig. 7. Merging process for interconnection feasibility test.

After this merging process, those parts that cannot be connected or disconnected will be merged together to form a virtual node called supernode. Therefore, the original liaison graph can be transformed into a simplified form with much less number of supernodes. A practical example for this merging process is illustrated as below.

Example: Merging Process for an AFI

A servo-motor assembly and its liaison graph are shown in Fig. 8 and Fig. 9. In Order to illustrate the merging principle, lets consider l_{15} (P8,P12):

A-paths(P8)={(P2->P8),(P1->P8)},
GIM[A-paths(P8)]={(-Z,0),(+Z,0)};
A-paths(P12)={(P1->P12),(P2->P12)},
GIM[A-paths(P12)]={(+Z,5gw),(-Z,7gw)};
Assume $f(l15)$=2gw for connection and disconnection
then f(P8)=(+Z,2gw), f(P12)=(+Z,2gw).
since f(P8)=(+Z,2 gw) ∈ *GIM*[(A-paths (P8)] and 2gw>0 thus P8 has no force-deliverable A-paths. Thus l_{15} violates the interconnection feasibility test and P8 and P12 are merged together.

Following the same margining process, those nodes associated with the liaisons that violate the interconnection feasibility test are all merged together. The supernodes formed after the merging process is shown in Fig.10.

4. Complexity

Because in general the liaison graph of an assembly with n parts can have $O(2^n)$ cut-sets, the worst case time complexity of the required geometric reasoning is $O(2^n)$. The geometric reasoning of each cut-sets usually involves local freedom of motion and global path constraint tests. The worst case of time complexity for global test for all critical directions for all contacts is $O(N^4)$. Thus the worst case time complexity without any physical reasoning will be $O(N^4 2^n)$. Now lets consider the complexity after physical reasoning. The maximum number of liaisons of a liaison graph with n parts is $n(n-1)/2$ which is $O(N^2)$. The time complexity for the interconnection feasibility test of each liaison is $O(N^2)$ for finding all the possible A-paths. then the worst case time complexity of merging process is $O(N^4)$. Assume after merging process, the number of nodes is m, then the worst case time complexity of geometric reasoning is $O(N^4 2^{N/c})$ where $c = n/m$. Thus the worst case time complexity by using the merging process is $O(N^4 + N^4 2^{N/c})$.

From our experiment, the value of c is usually greater than one. The time complexity is reduced by a exponential factor c for paying only polynomial time complexity. For example, after the merging process, the original liaison graph of the servo-mtor can be transformed into a very simple form called abstract liaison graph, $\tilde{G}_L(A)$, as shown in Fig. 10. The number of nodes of the original liaison graph is 13. The number of nodes of $\tilde{G}_L(A)$ is now 5, i.e., c= 13/5= 2.6. Roughly speaking, the required geometric reasoning is reduced from 2^{13} to 2^5 times.

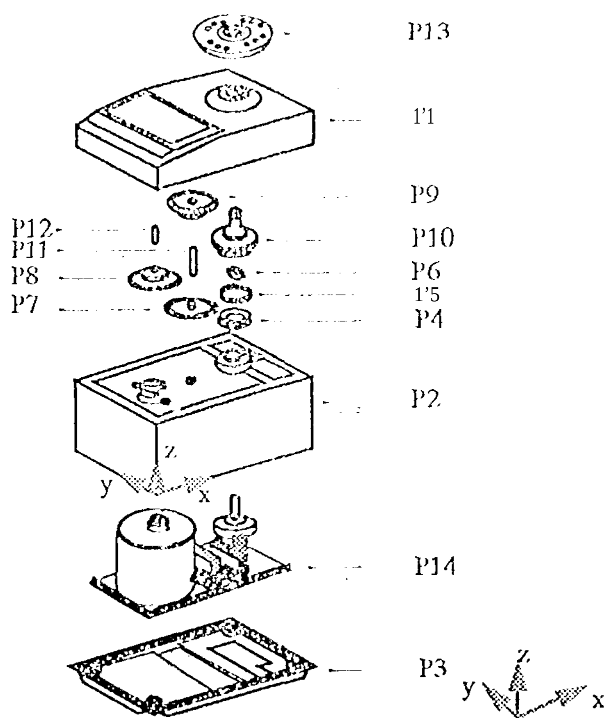


Fig. 8. An exploded view of a servo-motor assembly

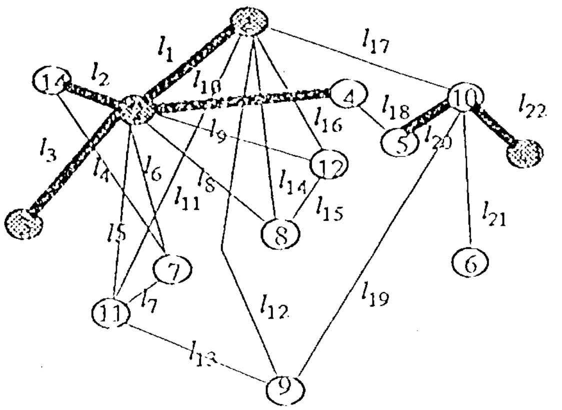


Fig. 9. Liaison graph of the servo-motor assembly.

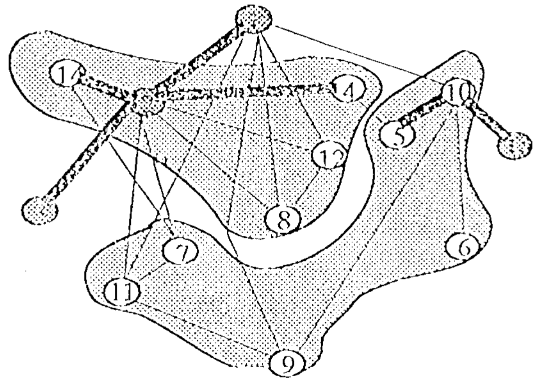


Fig. 10. Abstract liaison graph of servo-motor assembly after merging process.

5. Conclusion

In this paper, the physical reasoning of interconnection forces is considered and incoporated with a developed assembly planning method called backward assembly planning. With the physical reasoning of the required interconnection forces, many computationally expensive geometric reasoning can be avoided in advance to increase the efficiency of the assembly planning. Also by considering the generalized interconnection feasibility, the assembly planner can generate reversible assembly sequences for both assembly and disassembly planning. Of course with the consideration of forces factor during assembly task, the assembly planning is brought much closer to the real environment.

Acknowledgment

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